

TOUGH CARBON FIBER COMPOSITES BY HYBRIDIZATION WITH SELF-REINFORCED COMPOSITES

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Summary

While the interest in carbon fiber composites for automotive applications is rapidly increasing, their high cost and low failure strain or toughness continue to impede their widespread use. Both factors can be improved by hybridizing carbon fibers with a material that offers both ductility and reduced cost. In this work, the hybridization with highly oriented polypropylene tapes was investigated. Hybrid co-woven cloths of carbon fiber/polypropylene (PP) prepregs and oriented PP tapes were used to make hybrid composites with carbon fiber volume fractions of 3, 8 and 15%. Increasing the fraction of carbon fiber significantly increased tensile modulus, while the ultimate failure strain of 20% was maintained. Only at a carbon fiber fraction of 15% did the tensile failure strain fall significantly, but importantly, this hybrid composite still possessed good impact resistance. All hybrid composites maintained excellent thermoformability, making these composites suitable for high-volume production.

1 INTRODUCTION

Carbon fiber-reinforced composites have excellent mechanical performance as well as good specific properties. They are increasingly used in many applications, such as aerospace, wind energy and sports applications. The automotive industry is expected to become the next large composite market for carbon fiber-reinforced composites. Currently, the main limitations preventing carbon fiber composites to be widely applied in mass produced cars, is their lack of toughness and their high price.

Carbon fibers have an intrinsically low failure strain of 1.5-2%. Combined with their low off-axis properties, this leads to early damage initiation and poor impact

performance. While many investigations have tried to improve this early damage initiation (ref. 1), the achieved toughness improvements remain too small for automotive purposes. A promising approach that can lead to both large toughness improvements and reduced cost, is the concept of fiber hybridization. This means a second type of fiber, which is more ductile, is added to the carbon fiber composite to increase the overall toughness. At the same time, this will lead to a cost reduction, as most fibers are cheaper than carbon fiber.

It is well recognized that increased dispersion of the two fiber types leads to improved mechanical properties (ref. 2, 3). These fibers can be combined in three different configurations, in order of increased dispersion: interlayer, intralayer and intrayarn. Interlayer hybrid composites are straightforward to produce, but have a low dispersion. Intrayarn hybrid composites have a high dispersion, but can be expensive and difficult to obtain commercially. Intralayer hybrid composites may offer the right balance between commercial availability, price and mechanical performance. Several authors have proven that they have better impact resistance than interlayer hybrid composites (ref. 4, 5).

Historically, the typical fiber to hybridize with carbon fiber is glass fiber (ref. 3, 6, 7, 8). The toughness improvements with glass fiber are however limited as glass fiber also has a relatively low failure strain of about 3%. Larger improvements can be achieved by hybridizing with a more ductile fiber type, such as highly drawn PP fibers or tapes. Self reinforced polypropylene composites, SRPP (ref 9), produced from oriented PP tapes by a process termed hot compaction, have been shown to offer outstanding toughness combined with a very low density.

This paper presents the intralayer hybridization of carbon fiber prepreg tapes with oriented PP tapes to produce a hybrid composite using the hot compaction technology. The tensile behavior and impact resistance of these novel hybrid composites is explored, along with their thermoformability.

2 MATERIALS & METHODS

2.1 Materials

Highly drawn polypropylene (PP) tapes with a stiffness of 6.9 ± 1.2 GPa and a strength of 589 ± 24 MPa (ref. 10) were provided by Propex Fabrics (Germany). Unidirectional T700 carbon fiber polypropylene (CFPP) preregs were sourced from Jonam Composites and have a nominal fiber volume fraction of 40%. These preregs are 190 μ m thick and 100 mm wide, but were slit down to 3 mm width.

The CFPP preregs were co-woven by Propex Fabrics with the drawn PP tapes into a hybrid cloth. The CFPP preregs were inserted in the weft direction only, in three different ratios. The ratio was either 1 out of 8, 1 out 4 or 1 out of 2, leading to an estimated carbon fiber volume fraction of 3%, 8% and 15% respectively. As a reference material, a PP cloth without any CFPP preregs was woven as well.

Propex Fabrics GmbH also provided a 20 μ m thick PP film. This film has a melting point of 163°C and consists of the same PP grade as the drawn PP tapes.

2.2 Hot compaction

Eight woven layers were stacked in a (0-90-0-90)_s layup. The weft direction is labelled as the 0° direction, as it contains the CFPP tapes and is hence the stiffest and strongest direction. Note that the layup for the reference SRPP cloth is irrelevant, since the 0° and 90° are identical. To facilitate thermoforming, an interleaved film was added in between each hybrid cloth for the thermoforming samples. This was not done for the tensile and impact samples.

The layup was put in between two 1 mm thick aluminum cover plates and inserted into a preheated press at 188°C. This stack was hot compacted for 5 minutes at 40 bar pressure, after which it was cooled down to 40°C in 5 minutes.

2.3 Tensile tests

Quasi-static tensile tests were performed according to ASTM D3039. Tensile samples of 250x25mm were water jet cut to minimize damage to the edges. The strain was measured by averaging the surface strain with digital image correlation.

The tensile modulus was calculated as the slope between 0.1% and 0.3% strain. Two tensile strengths were calculated. The first strength value was related to the CFPP failure, while the second strength value coincided with final failure of the SRPP.

2.4 Impact tests

The impact behavior of these hybrid composites was investigated by performing falling weight impact tests on a Fractovis CEAST 6789. A hemispherical striker with a diameter of 20 mm falls down from a 1 m drop height onto the sample. The 100x100 mm sample was clamped by a ring with inner diameter of 40 mm and at a pressure of 6 bar. The mass of the striker was 26.17kg. The energy absorption was calculated from the surface underneath the load-displacement curve, until the load dropped to half of the peak load.

2.5 Thermoforming

Thermoforming trials were carried out on the hybrid composites at the University of Leeds by using a matched hemispherical mold with a 75 mm diameter. The hybrid composite plates were cut to a size of 150x150mm and were clamped by a 1 kN load in an oven which was preheated at 160°C. The temperature was allowed to equilibrate for 5 min, before the matched mold was closed using a speed of 50mm/min. Once closed, the force was kept on the samples until the oven, and sample, was cooled down.

3 RESULTS

3.1 Tensile behavior

The tensile behavior of the intralayer hybrid composites is shown in Figure 1, while the tensile modulus, tensile strength and ultimate failure strain of the hybrid composites is summarized in Figure 2. The carbon fiber failure occurs at 1.8% strain, but this does not lead to final failure of the composite. The SRPP fraction is still able to continue carrying stress up to a final failure strain of about 20%. This is not the case for the 15% cloth, where the ultimate failure strain was reduced to 6.3%. This reduced failure strain is related to the failure development in these hybrid composites. In the 3% and 8% cloth, the CFPP failure is followed by a gradual propagation of delamination, which spreads over the entire sample. This allows the SRPP fraction to fully extend over its entire length. In the 15% cloth, the high fraction

of CFPP prepregs leads to more matrix between the layers because the prepregs contain more PP than needed. This generates better bonding but also prevents the delamination from occurring, which leads to localization of the strain in a small region around the location where the carbon fiber layer broke. Locally, the failure strain of PP tapes of about 20% is still reached, but the global failure strain of the composite is limited, see Figure 2c. This shows there is an upper limit of carbon fiber fraction that still leads to high ultimate failure strains.

The stiffness increases with increased carbon fiber volume fraction, but this does not occur as fast as expected based on the linear rule-of-mixtures, see Figure 2a. This indicates that carbon fiber misalignment may have occurred due to the shrinkage of the drawn PP tapes during hot compaction. Figure 2b demonstrates that the tensile strength of the CFPP peak increases with increased carbon fiber volume fraction, while the strength of the SRPP peak decreases. For the 3% cloth, the SRPP peak is higher than the CFPP peak, meaning that the additional carbon fiber did not influence the overall strength. The CFPP and SRPP peaks have the same height in the 8% cloth. The 15% cloth has a higher CFPP peak, but the ultimate failure strain is reduced to 6.3%, see Figure 2c.

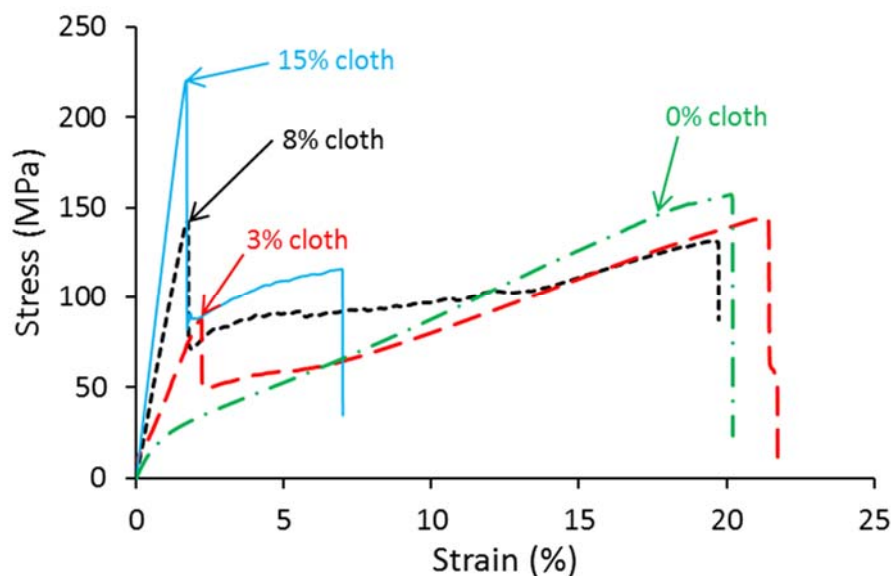


Figure 1: Representative tensile diagrams for the intralayer hybrid composites

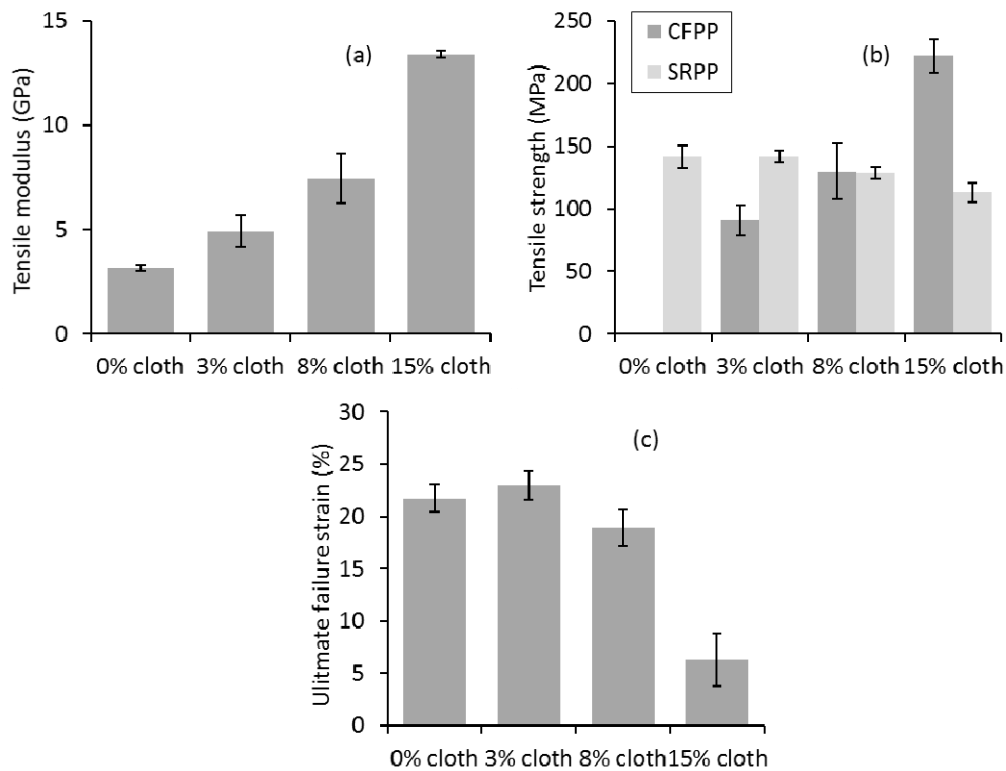


Figure 2: (a) Tensile modulus, (b) tensile strength, and (c) ultimate failure strain of the intralayer hybrid composites at various volume fractions of carbon fiber.

3.2 Impact resistance

Figure 3 shows that the addition of 3% carbon fiber did not reduce the absorbed energy compared to the 0% cloth. The impact resistance of the 8% and 15% cloth was reduced by about 40%. It is, however, remarkable that the strongly reduced tensile failure strain of the 15% cloth does not lead to a further reduction in the absorbed energy. The delaminations, which were crucial for the tensile behavior, did not play a major role in the energy absorption during impact.

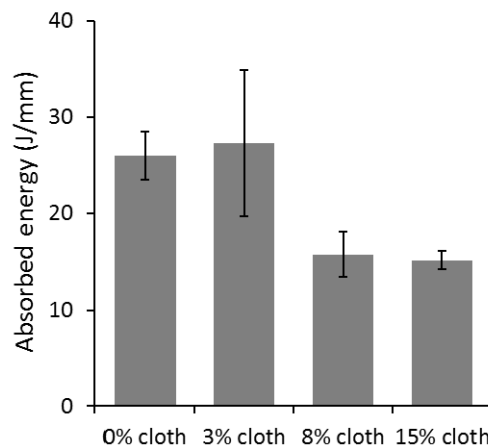


Figure 3: Absorbed energy during penetration impact tests

3.3 Thermoforming

Hot compacted SRPP can be easily thermoformed in various shapes, but the addition of continuous carbon fibers may hamper the thermoformability and so it was important to investigate this aspect. Therefore, thermoforming was tried out on the three hybrid composites (3%, 8% and 15% carbon fiber fraction) and the results are shown in Figure 4. All the hybrid cloths formed well at 160°C. Some stress whitening regions could be observed at the crown of the hemispheres of the 8% cloth, which may indicate some level of debonding, although it could also be because the sheet thickness did not exactly match the mold gap. These regions are also accompanied by a higher surface roughness, which may indicate that the stress whitening can be prevented by tuning the material thickness or the mold gap. Stress whitening, which is a typical damage feature of stretched PP, was not observed on the 3% and 15% cloth. In the latter case, the whitening may be hidden due to the dark color of the samples.

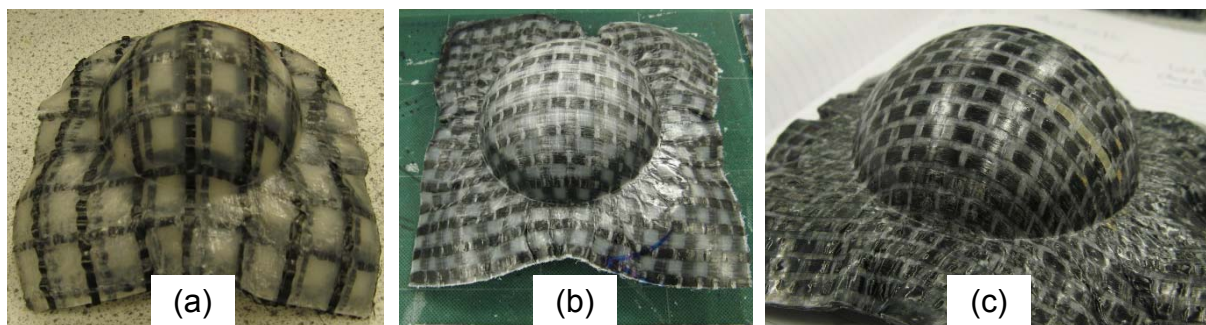


Figure 4: Hemispheres of intralayer hybrid composites after thermoforming: (a) 3% cloth, (b) 8% cloth, and (c), 15% cloth.

4 CONCLUSION

The mechanical performance and thermoformability of the intralayer hybrid SRPP/CFPP composites was investigated. The tensile behavior shows a carbon fiber peak, followed by a long and ductile SRPP tail. This type of behavior is made possible by stable growth of the delaminations between the two components after the CFPP failure. At 15% carbon fiber volume fraction, the additional PP in the preregs improved the bonding and prevented the delamination, leading to a strong decrease of the ultimate failure strain. The penetration impact performance was decreased by the addition of CFPP for 8% and 15% cloth, but the 15% cloth still performed similar to the 8% cloth. For these reasons 8% carbon fiber is considered the optimum

fraction. Finally, all hybrid cloths were shown to still possess excellent thermoformability. This new hybrid composite combines good tensile properties and impact resistance with excellent thermoformability. This makes it a promising material for mass production in automotive industry.

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